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Impact of Hypobarism During Simulated Transport on Critical Care Air Transport Team Performance

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14. ABSTRACT

Rapid, unacclimatized ascent to altitude results in a predictable fall in the partial pressure of oxygen and a reduction in arterial oxygenation. At 8000 feet, alveolar oxygen falls to 71 mmHg (barometric pressure of 564 mmHg). Under normal circumstances, this relative hypobaric hypoxia can be overcome by cardiac and pulmonary compensatory mechanisms. The added stress of caring for a critically ill patient and the physical demands may also impact the level of oxygen desaturation. During Critical Care Air Transport Team Advanced Course validation, three-member teams consisting of a physician, nurse, and respiratory therapist were approached regarding participation. Subjects were instrumented with a standard pulse oximeter with airworthiness approval. A forehead sensor was used to avoid motion artifact and interference with required tasks. The Environmental Symptoms Questionnaire IV (ESQ-IV) was completed by each participant (prior to flight at sea level and at the end of the 2-hour flight). Preflight data captured age, gender, height, weight, body mass index, smoking history, past medical history, and physical exercise history. The average and minimum pulse oximetry saturation (SpO_2) and heart rate values were determined over 15-minute intervals from baseline and throughout the first 75 minutes at altitude. Mixed model analysis was used to compare outcomes across the five intervals. F-tests were used to determine whether or not those outcomes changed – on average – during flight and t-tests determined whether there were statistically significant differences in demographic characteristics or ESQ variables between subjects who were ever hypoxic and those who did not suffer hypoxia ($SpO_2 < 90\%$). One hundred subjects were studied (65 men, 35 women), with a mean age of 34 years and body mass index of 26 m^2. At 8000 feet (564 mmHg), the mean SpO_2 fell from 98.7 ± 0.66 to 94.4 ± 0.34 (mean ± standard error). The lowest SpO_2 at baseline was 95.3 ± 0.41 falling to 88.8 ± 0.53 at 45 minutes at altitude. There were no differences in the rate of hypoxia based on gender, ethnicity, or race as well as between smokers and nonsmokers. Home elevation did not alter the incidence of hypoxemia. We did not observe any differences in the domains for cold, muscle, cardiopulmonary, tired, or well-being between subjects with and without hypoxemia. Hypobarism resulted in a predictable fall in SpO_2. There were no differences in ESQ-IV values between subjects with and without hypoxemia. No subject noted perceptions of hypoxia. None of the measured demographic variables predicted hypoxia. Monitoring over this 2-hour period was feasible and did not demonstrate significant hypoxia. Further studies during prolonged, tactical flights should be performed.

15. SUBJECT TERMS
Critical Care Air Transport Team, CCATT, hypobaria, hypoxia

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TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

Page

LIST OF TABLES

Page

1.0 SUMMARY

Rapid, unacclimatized ascent to altitude results in a predictable fall in the partial pressure of oxygen and a reduction in arterial oxygenation. At 8000 feet, alveolar oxygen falls to 71 mmHg (barometric pressure of 564 mmHg). Under normal circumstances, this relative hypobaric hypoxia can be overcome by cardiac and pulmonary compensatory mechanisms. The added stress of caring for a critically ill patient and the physical demands may also impact the level of oxygen desaturation.

During Critical Care Air Transport Team Advanced Course validation, three-member teams consisting of a physician, nurse, and respiratory therapist were approached regarding participation. Aspects of the trial were explained and informed consent was obtained. Subjects were instrumented with a standard, Food and Drug Administration-cleared pulse oximeter (Nonin 2500, Nonin Medical) with airworthiness approval. A forehead sensor was used to avoid motion artifact and interference with required tasks. Data from the oximeter, including pulse oximetry saturation (SpO_2), pulse rate, and signal quality, were stored to the oximeter's internal memory every 10 seconds. The Environmental Symptoms Questionnaire IV (ESQ-IV) was completed by each participant (prior to flight at sea level and at the end of the 2-hour flight). The ESQ-IV uses a 5-point Likert scale ranging from "not at all" to "extreme." Preflight data captured age, gender, height, weight, body mass index, smoking history, past medical history, and physical exercise history. Data were analyzed by 15-minute flight segment. The average and minimum SpO_2 and heart rate values were determined over 15-minute intervals from baseline and throughout the first 75 minutes at altitude. We also determined the median, interquartile range (25-75% percentile), and range of values. Mixed model analysis was used to compare outcomes across the five intervals. F-tests were used to determine whether or not those outcomes changed – on average – during flight and t-tests determined whether there were statistically significant differences in demographic characteristics or ESQ variables between subjects who were ever hypoxic and those who did not suffer hypoxia ($SpO_2 < 90\%$).

One hundred subjects were studied (65 men, 35 women) with a mean age of 34 years and body mass index of 26 m^2. At 8000 feet (564 mmHg), the mean SpO_2 fell from 98.7 ± 0.66 to 94.4 ± 0.34 (mean ± standard error). The lowest SpO_2 at baseline was 95.3 ± 0.41 falling to 88.8 ± 0.53 at 45 minutes at altitude. There were no differences in the rate of hypoxia based on gender, ethnicity, or race as well as between smokers and nonsmokers. Home elevation did not alter the incidence of hypoxemia. We did not observe any differences in the domains for cold, muscle, cardiopulmonary, tired, or well-being between subjects with and without hypoxemia.

Hypobarism resulted in a predictable fall in SpO_2. There were no differences in ESQ-IV values between subjects with and without hypoxemia. No subject noted perceptions of hypoxia. None of the measured demographic variables predicted hypoxia. Monitoring over this 2-hour period was feasible and did not demonstrate significant hypoxia. Further studies during prolonged, tactical flights should be performed.

2.0 BACKGROUND

Rapid, unacclimatized ascent to altitude results in a predictable fall in the ambient partial pressure of oxygen and consequently a reduction in alveolar and arterial oxygenation. A number of other environmental factors involved in low-altitude flight including low humidity, noise, and vibration all have negative consequences on human physiology. In addition to these environmental factors, hypobarism at 8000 feet reduces alveolar oxygen to 71 mmHg (barometric pressure of 564 mmHg). Under normal circumstances, this relative hypobaric hypoxia can be overcome by cardiac and pulmonary compensatory mechanisms, including an increased heart rate or stroke volume, tidal volume, and respiratory rate. However, each individual has his/her own response to hypoxia based on physical condition, resident altitude, and genetics. The added stress of caring for a critically ill patient and the physical demands may also impact the level of oxygen desaturation.

Recent studies have demonstrated that at altitudes as low as 5000 feet, hypoxemia and symptoms of high-altitude illness have been seen in normal volunteers and aircrew [1-6]. Nishi et al. demonstrated that hypoxemia was common during rotor-wing flights in aircrews with many changes occurring below 5000 feet [1]. The work by Muhm et al. [2] suggests that commercial aircraft should routinely be pressurized to a minimum of 6000 feet versus the current standard of 8000 feet. Above this altitude, headache, fatigue, malaise, and shortness of breath were all more frequent. Current doctrine requires that pilots and crew use oxygen at altitudes >10,000 feet, while at lower altitudes, oxygen is not required.

These recent findings suggest that with the wide range of ages and physical conditioning of Critical Care Air Transport Team (CCATT) members, some caregivers could suffer hypoxemia at normal flight altitudes. The added physical stress of the caregiver may result in more significant hypoxemia than seen in studies of normal, sedentary volunteers. Under these circumstances, the abilities of a caregiver could be compromised.

We hypothesized that the level of oxygen desaturation observed at 8000 feet would vary between caregivers. We also sought to determine the relationship between the presence of oxygen desaturation and the results of the Environmental Symptoms Questionnaire IV (ESQ-IV).

3.0 METHODS

This was a prospective, observational study of CCATTs during simulated training flights.

During normally scheduled CCATT Advanced Course validation, three-member teams consisting of a physician, nurse, and respiratory therapist were approached by one of the non-Department of Defense investigators regarding participation in the trial. Aspects of the trial were explained at the beginning of the 2-week course, giving the participants over a week to accept or decline participation as a research subject. Training flights are accomplished on Thursday of the second week of training. Following presentation of the informed consent document and answering study-specific questions, those subjects interested in participation signed the informed consent document.

On the morning of the training flight, subjects were instrumented with a standard, Food and Drug Administration-cleared pulse oximeter (Nonin, Nonin Medical, Plymouth, MN) with airworthiness approval. A forehead oximetry probe was used to avoid problems of motion artifact with finger sensors. Additionally, the forehead probes did not restrict movement or interfere with tasks associated with the training flight. Data from the oximeter, including pulse

oximetry saturation (SpO_2), pulse rate, and signal quality were stored resident to the internal memory of the device. Signals were recorded continuously with a recording every 10 seconds. All data were downloaded at the end of the flight. Oximeters were incapable of collecting subject identifiers and used a unique identifying number to link data to questionnaires.

The ESQ-IV was completed independently by each participant at separate time points. The ESQ-IV is a validated survey that is used to determine the effects of altitude on participants, based on their perception of symptoms they are experiencing before and after the flight. The ESQ-IV was completed prior to flight at sea level while the participants had SpO_2 monitored. At the end of the 2-hour flight, the ESQ-IV was repeated.

The ESQ-IV use a 5-point Likert scale ranging from "not at all" to "extreme." Preflight subjects also completed a demographics questionnaire that captured age, gender, height, weight, body mass index (BMI), smoking history, past medical history, and physical exercise history. Baseline, SpO_2 and resting heart rate were also recorded during completion of the questionnaire.

Each subject received a unique participant identifier number allowing investigators to link the data from the ESQ-IV questionnaire, the demographics questionnaire, and the oximeter. Data were analyzed by 15-minute flight segment. The average and minimum SpO_2 and heart rate values were determined over 15-minute intervals starting at baseline and throughout the first 75 minutes at altitude. We also determined the median, interquartile range (25-75% percentile), and range of values. Mixed model analysis was used to compare outcomes across the five intervals. F-tests were used to determine whether or not those outcomes changed – on average – during flight. We also used t-tests to determine whether there were statistically significant differences in demographic characteristics or ESQ variables between subjects who were ever hypoxic and those who did not suffer hypoxia during the experiment.

Based on the work by Muhm et al. [2] demonstrating a mean fall in SpO_2 in seated aircraft passengers of 4.4%, we predicted 100 subjects would be required to detect a difference in SpO_2 between caregivers (those who developed hypoxia and those who did not) with a power of 80% at a significance of 0.5. Power was based on SpO_2, not on ESQ-IV, data.

4.0 RESULTS

One hundred individuals participated in the trial; 110 potential subjects were approached and 100 signed an informed consent document. Complete oximetry data were successfully obtained from all subjects. SpO_2 data were aggregated into 15-minute sextiles. The mean, median, 25-75% percentiles, and range were determined This included the baseline time at normal atmospheric pressure, ascent, cruising altitude, and descent.

Figures 1-5 represent the data for SpO_2 and heart rate. Figures 1 and 2 describe the mean SpO_2 and nadir SpO_2 during the sextiles of measurement. Tables 1 through 5 with each figure provide the data mean and standard error (SE). In each figure, the plot shows the distribution of subject-specific mean SpO_2 values averaged over the first 15 minutes at baseline and over consecutive 15-minute periods at 8000 feet. The diamonds indicate the overall mean values (also summarized in the tables). The horizontal lines inside the boxes show the median values; the boxes themselves show the interquartile range (from the 25^{th} percentile to the 75^{th} percentile). The "whiskers" attached to the boxes run from the lowest to the highest values.

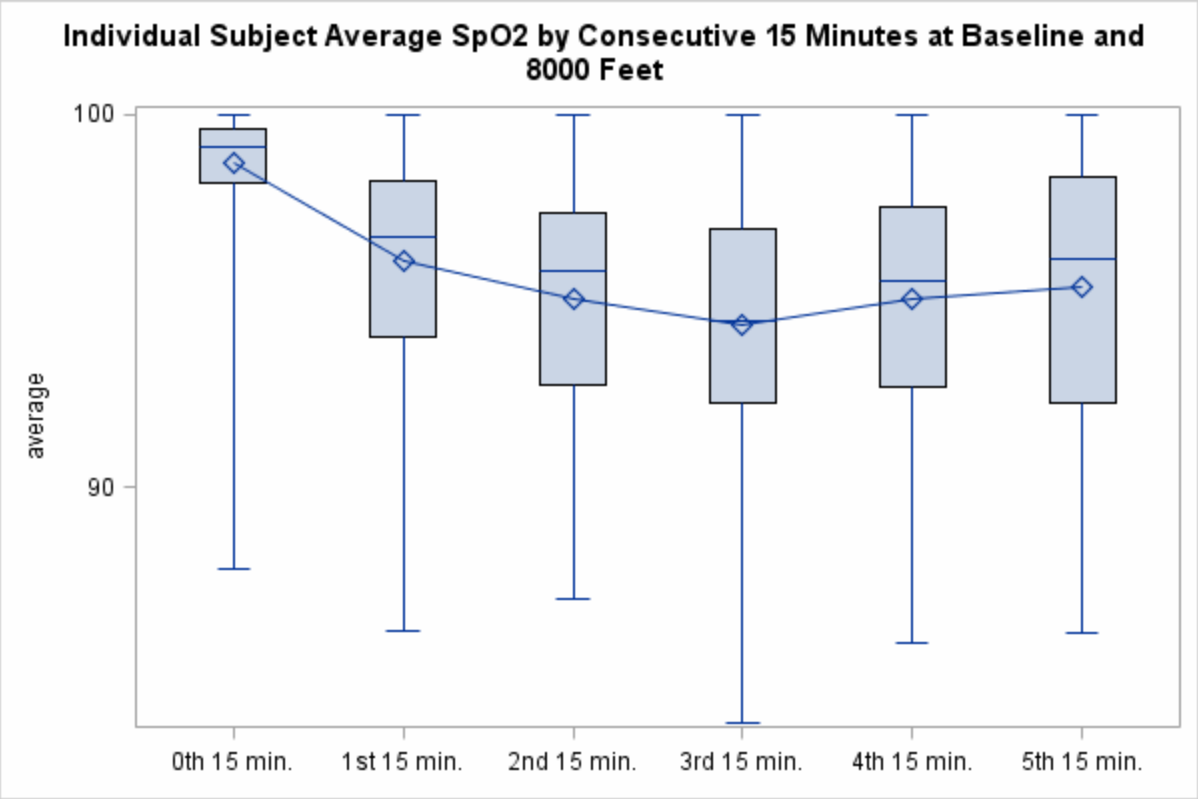

Figure 1. Average SpO_2 at baseline and every 15 minutes during flight.

Table 1. Average SpO_2 at Baseline and Every 15 Minutes During Flight

Phase	Mean	SE
0^{th} 15 min (baseline)	98.7	0.66
1^{st} 15 min @ 8000 ft	96.1	0.28
2^{nd} 15 min	95.0	0.33
3^{rd} 15 min	94.4	0.34
4^{th} 15 min	95.0	0.31
5^{th} 15 min	95.4	0.36

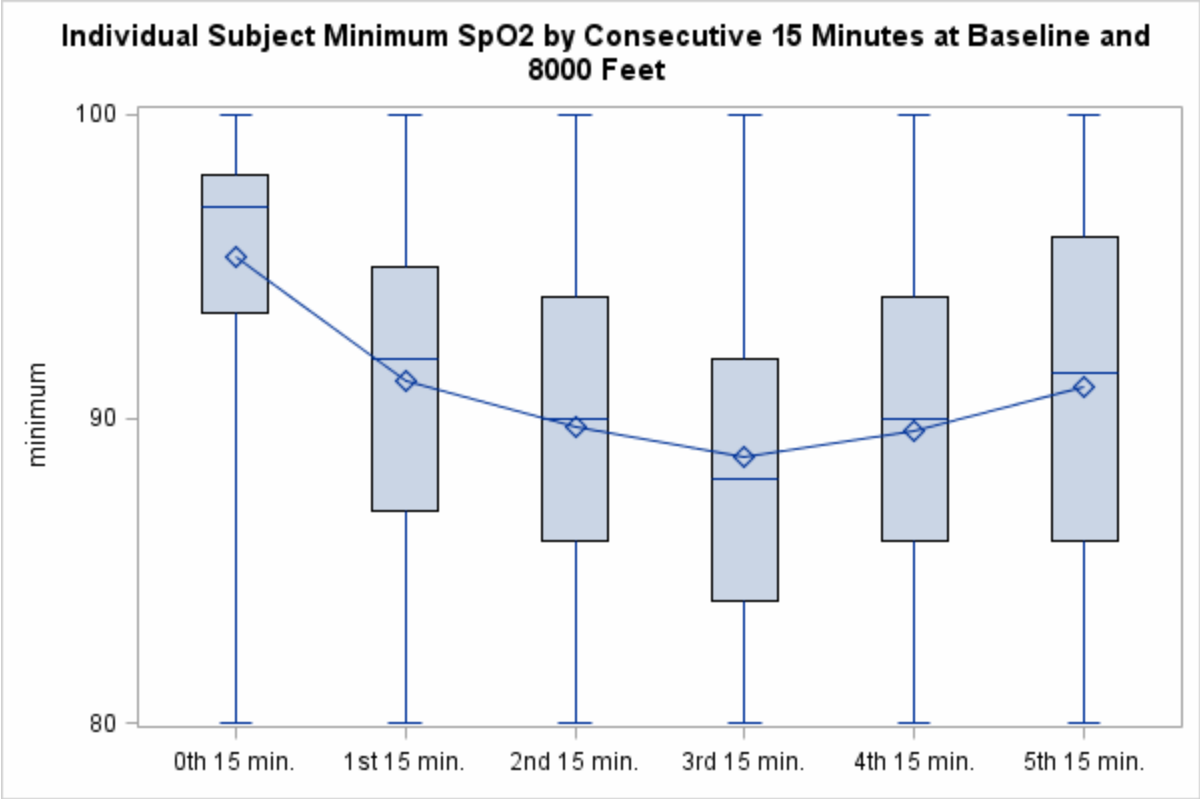

Figure 2. Lowest SpO_2 at baseline and every 15 minutes during flight.

Table 2. Lowest SpO_2 at Baseline and Every 15 Minutes During Flight

Phase	Mean	SE
0^{th} 15 min (baseline)	95.3	0.41
1^{st} 15 min @ 8000 ft	91.3	0.52
2^{nd} 15 min	89.8	0.53
3^{rd} 15 min	88.8	0.53
4^{th} 15 min	89.6	0.54
5^{th} 15 min	91.1	0.62

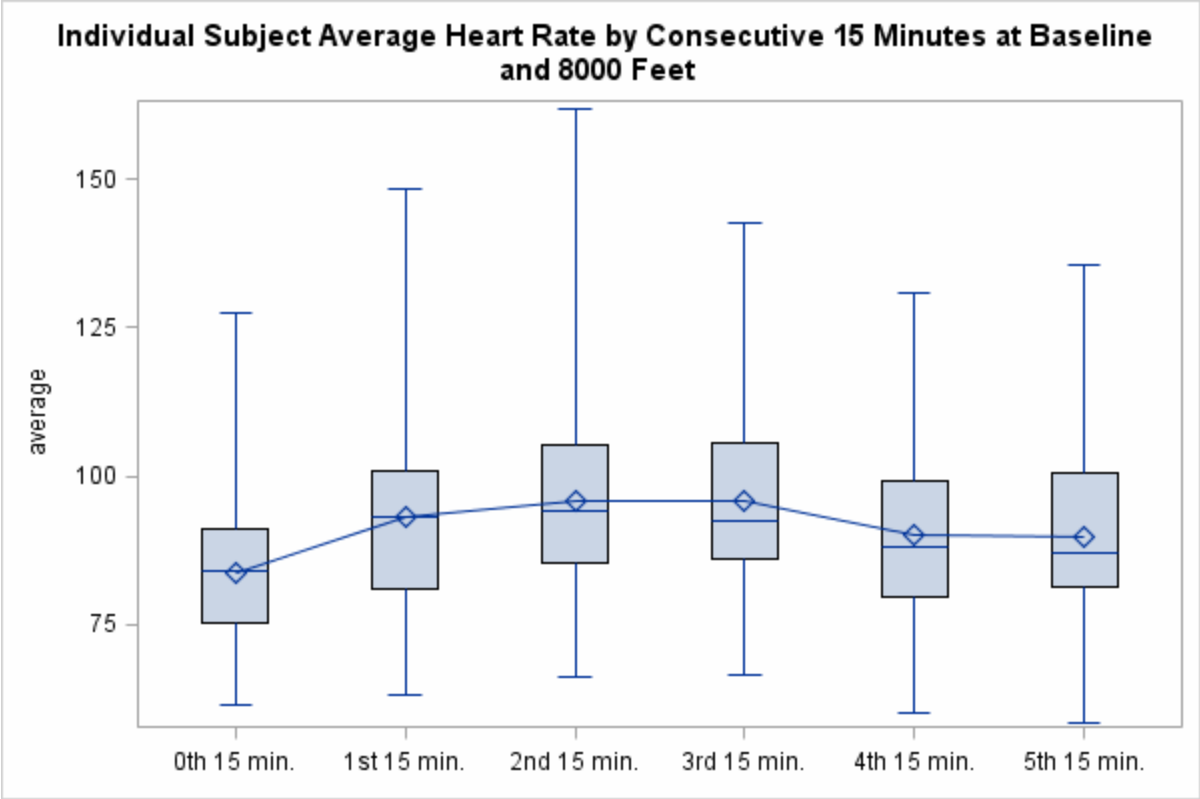

Figure 3. Average heart rate at baseline and every 15 minutes during flight.

Table 3. Average Heart Rate at Baseline and Every 15 Minutes During Flight

Phase	Mean	SE
0^{th} 15 min (baseline)	83.7	1.21
1^{st} 15 min @ 8000 ft	92.9	1.59
2^{nd} 15 min	95.9	1.66
3^{rd} 15 min	95.7	1.58
4^{th} 15 min	90.2	1.51
5^{th} 15 min	89.7	1.51

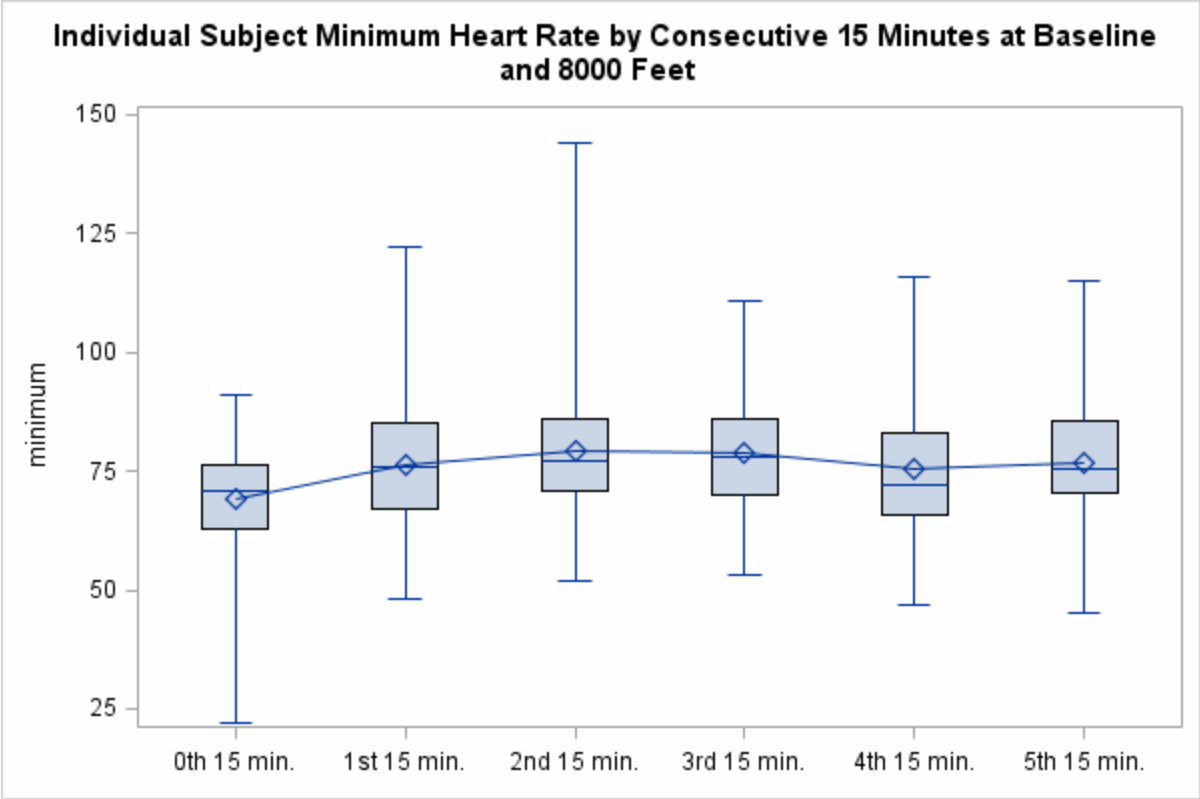

Figure 4. Minimum heart rate at baseline and every 15 minutes during flight.

Table 4. Minimum Heart Rate at Baseline and Every 15 Minutes During Flight

Phase	Mean	SE
0th 15 min (baseline)	69.3	1.13
1st 15 min @ 8000 ft	76.3	1.36
2nd 15 min	79.2	1.47
3rd 15 min	78.2	1.18
4th 15 min	75.4	1.29
5th 15 min	76.7	1.31

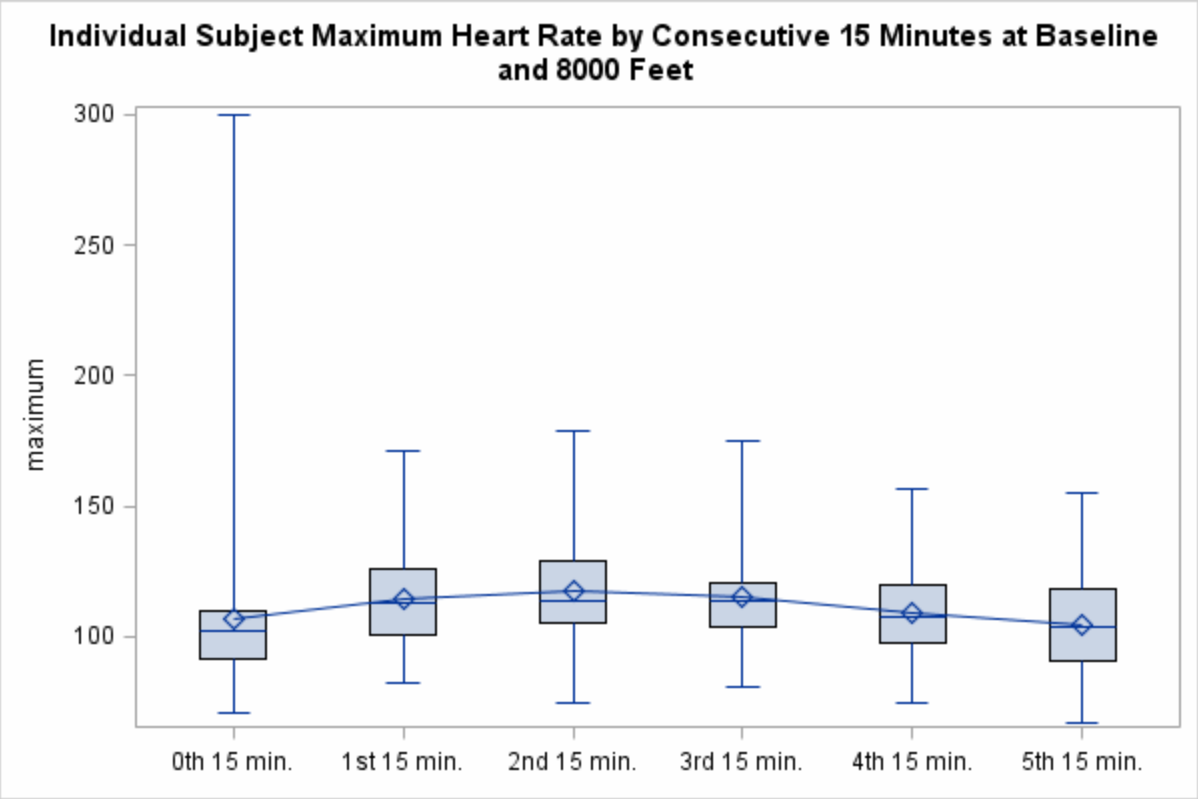

Figure 5. Maximum heart rate at baseline and every 15 minutes during flight.

Table 5. Maximum Heart Rate at Baseline and Every 15 Minutes During Flight

Phase	Mean	SE
0^{th} 15 min (baseline)	106.9	3.19
1^{st} 15 min @ 8000 ft	114.5	1.86
2^{nd} 15 min	118.7	2.04
3^{rd} 15 min	115.5	1.88
4^{th} 15 min	109.5	1.66
5^{th} 15 min	104.7	1.87

We divided the subjects into two groups: group 1, subjects who developed mild hypoxia (SpO_2), and group 2, those with no hypoxia at 8000 feet. We compared the ESQ-IV data between these two groups (Table 6).

Table 6. Demographic and ESQ Variables Comparing Subjects with Any Evidence of Hypoxia at 8000 Feet to Those Without Evidence of Hypoxia at 8000 Feet

Variable	Hypoxic	Not Hypoxic	p-value
Male	17 (26.2%)	48 (73.9%)	0.39
Female	12 (34.3%)	23 (62.7%)	
Hispanic/Latino	3 (42.9%)	4 (67.1%)	0.40
Not Hispanic/Latino	25 (27.2%)	67 (72.8%)	
Black	0 (0.0%)	3 (100.0%)	0.56
White	27 (28.4%)	68 (71.6%)	
Tobacco Use Yes	4 (26.7%)	11 (73.3%)	1.00
Tobacco Use No	25 (29.4%)	60 (70.6%)	
BMI	25.9	26.1	0.60
Age, yr	34.4	37.6	0.60
Residence Elevation, ft	672.6	781.7	0.73
INITIAL			
ESQ: Cold	0.59	0.39	0.53
ESQ: Muscle	1.55	0.32	0.26
ESQ: CardioPulm	1.72	0.03	0.25
ESQ: Tired	1.28	0.70	0.15
ESQ: Well-Being	5.42	5.65	0.79
POST			
ESQ: Cold	0.48	0.75	0.55
ESQ: Muscle	1.28	0.49	0.46
ESQ: CardioPulm	2.52	1.13	0.36
ESQ: Tired	1.21	1.07	0.79
ESQ: Well-Being	7.34	7.68	0.67
CHANGE			
ESQ: Cold	-0.10	0.35	0.31
ESQ: Muscle	-0.28	0.17	0.09
ESQ: CardioPulm	0.79	1.10	0.48
ESQ: Tired	-0.07	0.37	0.69
ESQ: Well-Being	1.93	2.04	0.90

5.0 DISCUSSION

This study is the first, to our knowledge, that has monitored the impact of hypobarism on caregivers in a working environment. We were able to show that monitoring subjects with a forehead oximetry sensor is feasible without causing undue restriction of required tasks. The findings are in concert with those of Muhm et al., who demonstrated that ascent to 8000 feet is associated with an average fall in SpO_2 of 4.4% [2].

In our study, a wide range of caregivers was studied during a critical care simulation caring for two subjects. The mean fall in lowest recorded SpO_2 was 6.5% and could reflect the impact of workload on oxygenation. The mean fall in SpO_2 in our study was only 4.3%. The study by Muhm et al. evaluated aircraft passengers seated in a simulated aircraft. That study also had a much longer period of observation than ours and included serving study participants a

meal. Post-prandial time frames and sleep were associated with lower SpO_2 [2]. In our trial, the subjects were caregivers, on their feet for most of the study performing low- to moderate-level physical and moderate-level intellectual tasks. It is possible that these tasks increased physiologic demands and resulted in lower SpO_2.

We also demonstrated the anticipated circulatory compensation for hypobaric hypoxia. Mean heart rate increased by 12%, which likely compensated for a fall in oxygen delivery caused by the fall in SpO_2 by an increased cardiac output. We did not measure stroke volume or blood pressure, but at these conditions an increase in heart rate is sufficient to restore normal oxygen delivery.

Interestingly, there was no difference in the rate of hypoxia between smokers and nonsmokers. This may reflect subject age and the variable impact of smoking on pulmonary function. Alternatively, we may not have studied sufficient numbers to detect a difference. There were also no differences in those who did and did not develop hypoxemia based on gender, ethnicity, or race. Most subjects resided at elevations less than 1000 feet from sea level, and elevation of their home base did not alter the incidence of hypoxemia.

Each participant completed the ESQ-IV before and after the flight. We did not observe any differences in the domains for cold, muscle, cardiopulmonary, tired, or well-being between subjects with and without hypoxemia. This could be attributable to the sample size, short flight duration, and/or the relative minor degree of hypoxemia. The ESQ-IV was developed to assist in helping aircrew identify signs of hypoxia. It is likely that the ESQ-IV is more adept at detecting more severe hypoxia, such as what occurs with a slow decompression of aircraft that goes unnoticed save the hypoxic symptoms.

Under normal conditions, the hypoxia at less than 10,000 feet (3048 meters) above mean sea level has no apparent ill effects on passengers or aircrews. However, several hypoxic incidents have been reported in flights below 10,000 feet. Reports to the Directorate of Flying Safety of the Australian Defence Force concerning incidents of hypoxia occurring between 1990-2001 found that 4 of 27 incidents occurred at less than 10,000 feet. A survey of hypoxic events in Australian Army helicopter aircrews operating at altitudes of up to 10,000 feet reported that 40 of the 53 crew members experienced symptoms of in-flight hypoxia [4,5].

Nishi measured SpO_2 in aircrews operating UH-60J helicopters without a pressurized cabin at altitudes of up to 13,000 feet. The authors also surveyed 338 aircrew members operating aircraft with unpressurized cabins concerning their career in-flight hypoxic experiences. This paper demonstrated similar SpO_2 results to those we describe. Additionally, they found that at 13,000 feet, mean SpO_2 fell to 82%. A consequent increase in heart rate of 20% was also seen at this altitude [1].

Previous work using an anonymous survey to examine hypoxic symptoms during helicopter operations at below 10,000 feet found that both the number of symptoms suggesting hypoxemia and their incidence were greater in loadmasters than in pilots [5]. This was attributed to the greater physical activity levels of loadmasters. Thornton et al. reported that during routine sorties, the workloads of loadmasters increased 1.5-fold (compared to the resting state) and were greater than those of pilots [6]. The impact of performing mild physical exercise on SpO_2 was confirmed by Muhm et al., and an older study demonstrated a decrease in SpO_2 of 1% at ground level, a decrease of 4.3% at 7,000 feet, and a decrease of 5.5% at 9000 feet [5]. These data suggest that physical activity by crews might contribute to hypoxemia.

6.0 CONCLUSIONS

Our aim was to determine if there were subject characteristics that were associated with the development of hypoxia in individuals within a CCATT. The mean age of subjects was 33-34 years, and while there was a wide range of ages and BMI, these factors did not predict hypoxia. Of note, tobacco use in about a quarter of subjects also did not differentiate those with and without hypoxia. We demonstrated the feasibility of continuous SpO_2 monitoring in caregivers during routine care. Future studies should monitor caregivers during actual CCATT missions over prolonged time frames. The impact of sleep, turnaround times, and fatigue on oxygenation and subject performance should be considered. This study confirms the expected fall in SpO_2 at altitudes <10,000 feet

A follow-up study of caregivers in theater under operational conditions with prolonged flight times is required to adequately answer this question. This study proves that this can be accomplished. A follow-on study should also record caregiver activity (sleep, strenuous activity, etc.) using an activity monitor and record flight times, time between flights, and caregiver assessment of well-being.

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LIST OF ABBREVIATIONS AND ACRONYMS

BMI	body mass index
CCATT	Critical Care Air Transport Team
ESQ-IV	Environmental Symptoms Questionnaire IV
SE	standard error
SpO_2	pulse oximetry saturation